Design Project

MECH 323 Machine Design (Winter 2021)

Team Number	**2**

Phase Number	**4**

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1.0 Introduction

The purpose of this project is to design a gearbox to fit within the pre-built vehicle shown in Appendix B. The gearbox will fit onto either end of the vehicle and will transfer the rotation of the electric motor to the wheels through a set of gears. Throughout this project, the parameters of the gears and gearbox structure have been calculated through analysis of internal forces and the expected outcomes.

The types and sizes of the gears used correspond to the events that the vehicle will perform in. The gearbox designed is a 1-stage, shifting gearbox with one set of gears designed to maximize torque and another to maximize wheel speed for the hill climb and top-speed events, respectively. The hill climb event involves a curved ramp of radius 1.05 metre that has a maximum angle of incline of 45˚. The goal of this event is to have the vehicle climb as far as possible up the ramp. The top-speed event involves a flat track with a 4 metre accelerations zone, followed by a 2-metre timing zone. The goal of this event is to achieve the highest speed possible with the timing zone. Diagrams for each events' track can be found in Appendix C and Appendix D for the top speed and hill climb events, respectively. On top of the two ranked events, the vehicle must complete the super endurance event. This involves continuous operation of the vehicle, at the selected slip-point, for 5 years. The forces experienced over this long duration are the cause of many selected design parameters for this gearbox. All components have been designed to allow competitive performance in both the hill climb and top speed events while still being reliable enough to withstand the forces during the super endurance event.

This final phase of the project will detail all the final design components as well as offer justification for the design choices made. From the properties of the gears, shape of the shafts, selection of the bushings, and design of the housing; all pieces have undergone development throughout the design process.

2.0 Gearbox Design

The final design of our gearbox components takes into consideration the 3D printing and material change that will follow this phase of the project. Up until this point, the components were modelled as being made of AISI 4130 Steel. To allow for easy prototyping and testing of the design, the components will be printed using ABS plastic. The material properties vary greatly as well. The plastic has significantly lower stiffness and strength; however, the super endurance event will not be tested. An image of the complete gearbox assembly can be found below in Figure 1.

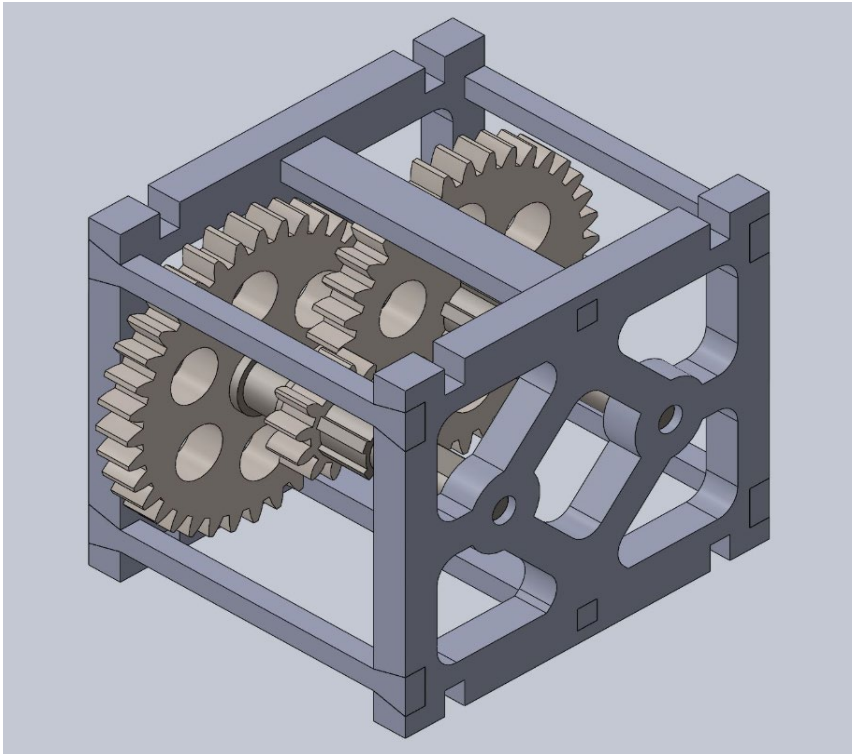


Figure 1: Rendered CAD model of the entire gearbox assembly. Enclosure shown in grey, and gears/shafts shown in brown.

2.1 Input and Output Shafts

Both the input and output shafts were made to fit properly within the gearbox housing structure. They both have splines to the sets of gears and are appropriate lengths to allow for the gear shifting to occur. By sliding the gears along the shaft, one set of gears disengage while another engages. This will change the gear ratio and optimize the vehicle for each event. Both shafts are 76 mm long including 6 mm of that length on either side fitting into the housing. Along with this, they both have one end with a 21 mm long d-shaft with the flat at a 1 mm depth and a diameter of 10 mm. This d-shaft will fit the sprocket which will connect to the driving chain. Images of both the input shaft and output shaft can be found below in Figure 2 and Figure 3, respectively.

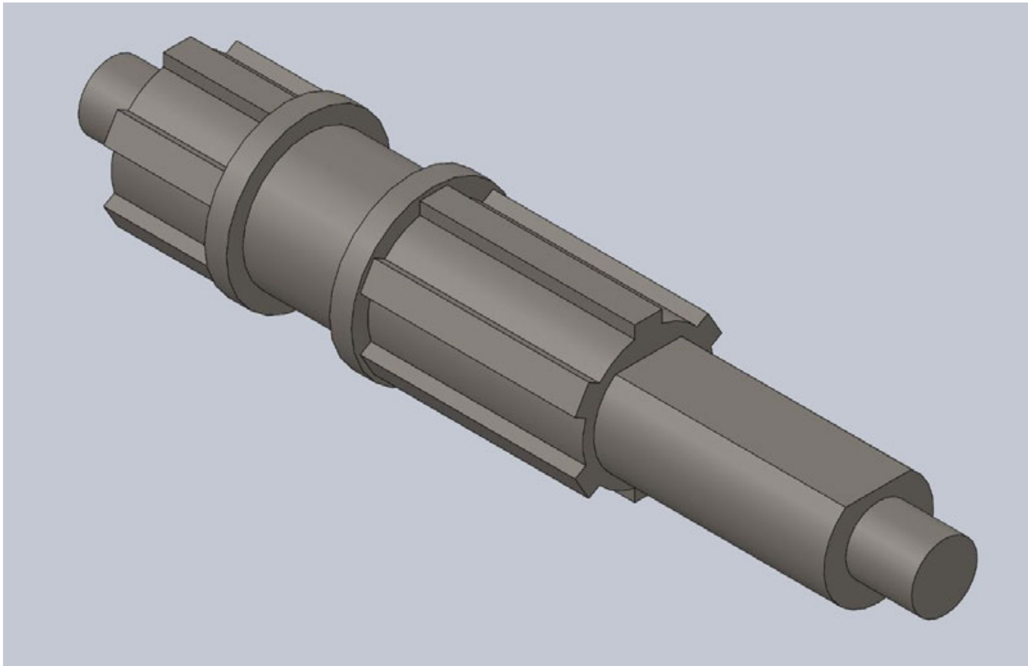


Figure 2: CAD renderings of the input shaft design. Keyways shown in yellow.

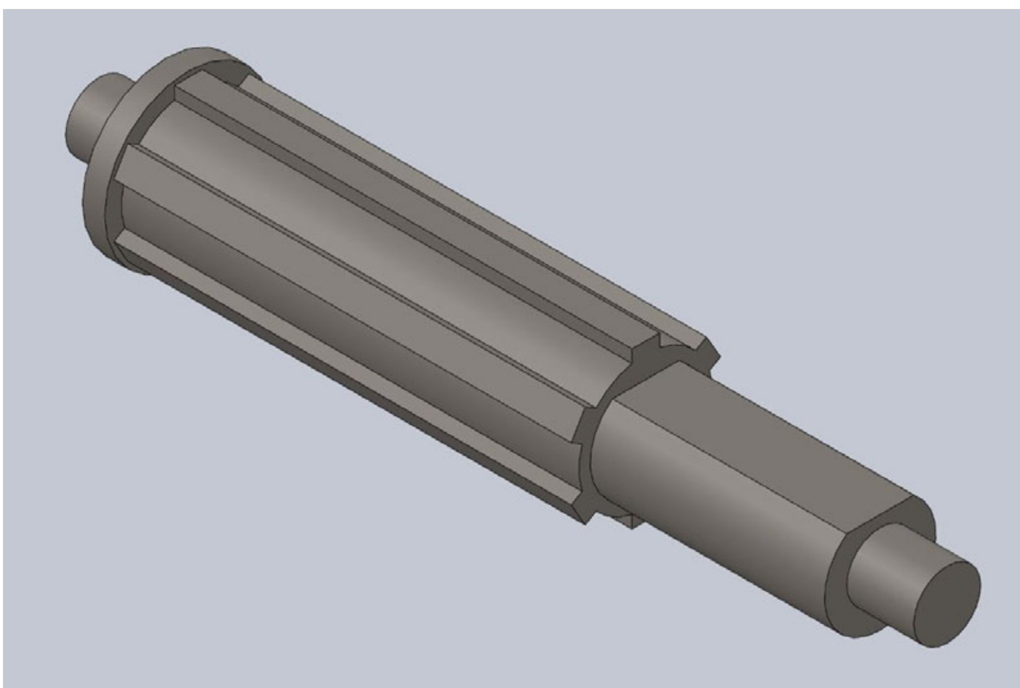


Figure 3: CAD renderings of the output shaft design. Keyways shown in yellow.

2.2 Spline Connection

For this phase of the project, the shafts and gears have been redesigned to connect using splines instead of the previously used keyway connections. This change is a result of the material change and the ABS plastic's significantly lower stiffness and strength. The splines provide a more uniform transfer of the torque and an equal distribution of the load from the gear to the shaft. The splines have a width of 2.5 mm and a depth of 1.13 mm for both shafts and all gears. All sections of the shafts that have the splines have a diameter of 12 mm.

2.3 Bushing Selection

The bushings that were selected for this design are the Oil-Embedded 841 Bronze Sleeve Bearings. These will fit on the 6 mm end sections of the shafts and within the 9 mm housing slots. The length of the bearings is 6 mm which will properly fit the shaft section and the 6 mm long cut-out section of the 8 mm thick housing. The part number of the bearings is: 6658K725 and they cost $1.10 each. For the four bearings needed for the design, the total cost will be $4.40 before taxes, shipping, etc. An image of the bearing is shown below in Figure 4.

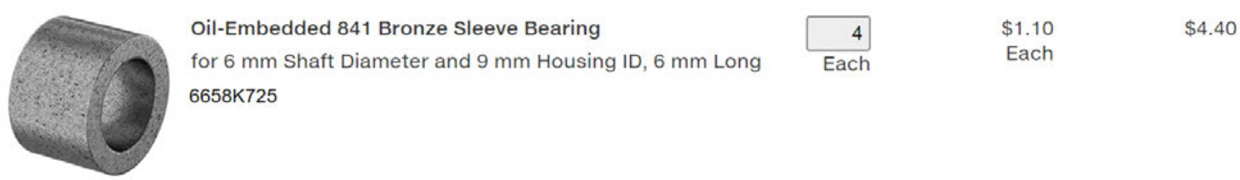


Figure 4: Image of the Oil Embedded 841 Bronze Sleeve Bearing selected for the design project. Dimensions, part number, and price shown.

2.4 Housing Design

The housing designed for this phase of the project had to meet many constraints while fitting all other components and supporting the loads of the gearbox. The pieces of the housing are made to be easily assembled without the need for connectors such as screws or bolts. The two side housing plates will sandwich the shafts (with bearings in place) and the connecting beams will fit in to resist expansion and compression forces on the housing. When the gearbox is fit within the test vehicle, the connecting beams will be locked in places and the housing will be a rigid structure. The dimensions of the housing will allow for proper fitment with the test vehicle and conform to all project constraints.

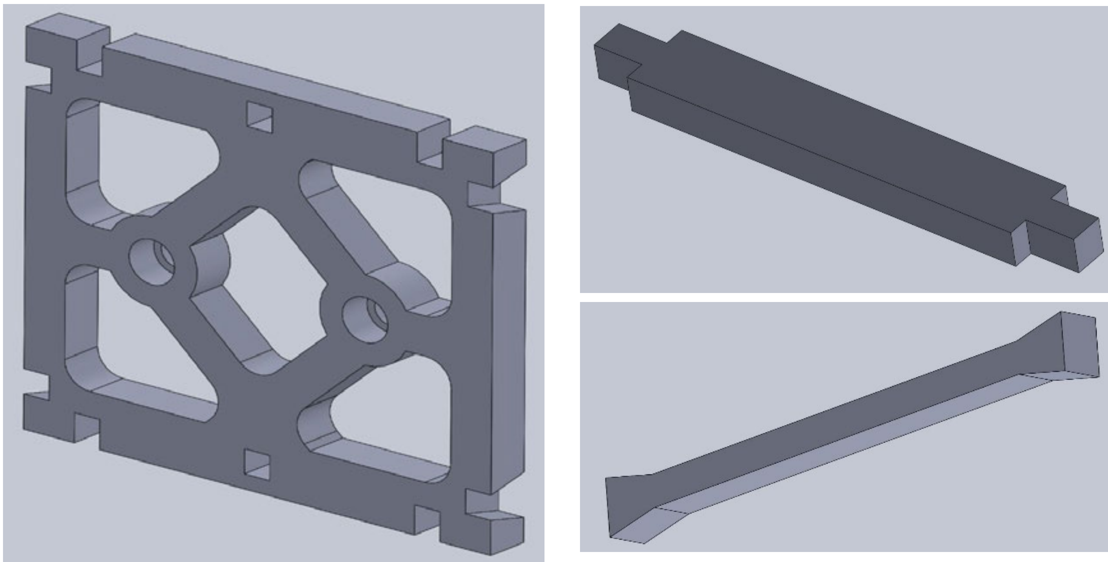


Figure 5: CAD renders of the gearbox design housing. The sides (left) have holes for the input and output shafts as well as notches for the connecting beams (right).

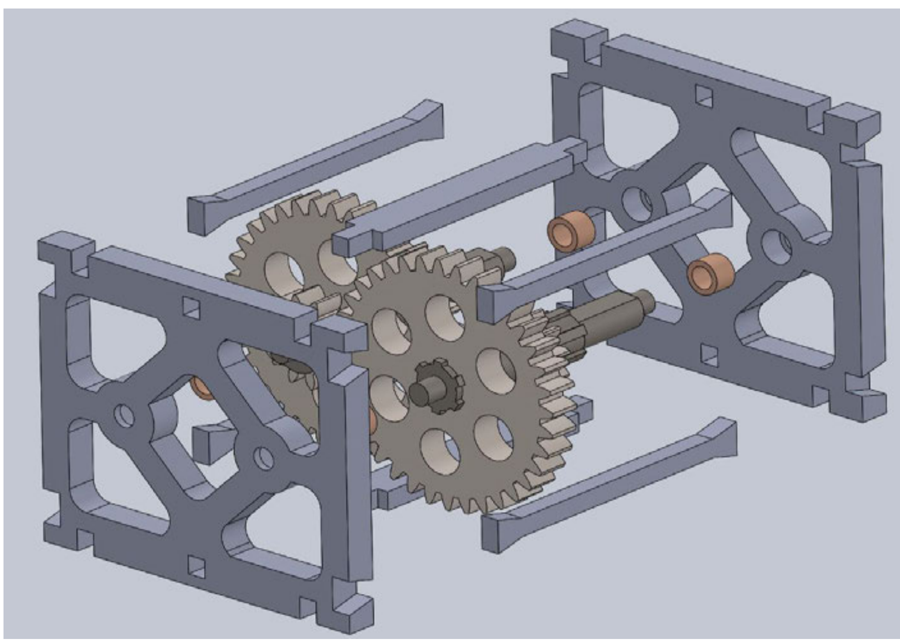


Figure 6: Exploded view of the gearbox assembly made in CAD. All housing components, shafts, gears, and bearings are shown.

2.5 Key Performance Metrics

All design features of the gearbox housing will be listed below in Table 1 and explanations will be given as to why those decisions were made.

Table 1: All design features that were added to the gearbox housing and the reasoning behind it.

Design Feature of Gearbox Housing	Explanation/Reasoning
Cut-out on housing sided for shafts	The cut-outs were added to house the bushings and the ends of the shafts. Together with the dovetail connecting beams they restrict the ends of the shafts in all three dimensions and hold them in place.
Diamond shape on the sides of the housing	The shape of the sides of the housing is designed to increase rigidity in the housing and support the forces created throughout the gearbox of the vehicle. The diamond shape connects the centers of all 4 edges of the housing sides which is creates a strong shape. Filling in the entire side would have significantly increased print time and material use while only adding limited structural support.
Corner connecting beams with dovetail-ends	The corner connecting beams of the housing resist expansion of the gearbox housing in the axial direction of the shafts. They do this with the dovetails wedging into the sides of the housing. With the shafts already resisting compression in the same direction due to the cut-outs, the gearbox is locked in place in the axial direction of the shafts.
Top and bottom non-dovetail connecting beams	The non-dovetail connecting beams located at the top and bottom of the housing sides add further resistance to compression of the gearbox in the axial direction of the shafts. Unlike the shafts themselves, which resist compression in the center axis of the housing sides, these connecting beams can effectively resist against moment forces on the sides of the gearbox due to their distance from the center. These components add further rigidity and support to the housing structure.
Rectangular cut-outs in the corners	The cut-outs in the corners of the housing design are left open for the test vehicle to connect to the gearbox. As altering the test vehicle is outside the scope of this project, the options for this connection was limited and therefore the simple was used.
Thickness of the housing sides	The housing sidewall thickness was decided upon to create a strong enough shape while also being thick enough to fit the bushings. On top of this, extra thickness was needed to constrict the shafts in between the two sides.

3.0 Evolution of the Gearbox

While small changes have been made to the gearbox throughout the duration of the design process, the overall design has been by and large the same since Phase 1. The decision to proceed with the design using a one-stage shifting gearbox was made in the first phase and has not been changed. As will be discussed in Section 5.0, a two-phase shifting gearbox would have allowed for further optimization of the gear ratios, however, this was not selected due to the additional complexity and reliability challenges that this would have introduced. Once the single-stage shifting gearbox was selected, the first important design consideration was the optimization of the gear ratios for both the top-speed and hill-climb events.

The optimization for the top speed gear ratio was done by first utilizing the Motor Torque vs. Motor Speed curve, denoted in Eq. 1 and 2.

$$For\ 0 < \omega < 45; \qquad T = 2.25 - \left(\frac{1}{180}\right) * \omega \tag{1}$$

$$For\ 45 < \omega < 200; \qquad T = 2 - \left(\frac{2}{155}\right) * \omega \tag{2}$$

Understanding that the vehicle will begin at rest, the motor torque could be adequately predicted. The motor will output an instantaneous torque just below the stall torque, before gradually decreasing as the motor speed increases. Using the input torque relationships described by Eq. 1 and 2, a gear ratio was then applied in order to determine the output torque of the design. Eq. 3, 4, and 5 were then used to predict the acceleration, velocity, and distance travelled of the vehicle, respectively.

$$a = T_P * r \tag{3}$$

$$v = \omega_P * r \tag{4}$$

$$d = \sum \frac{V_2^2 - V_1^2}{a} \tag{5}$$

Using a discrete summation approach where for each torque value velocity and acceleration are assumed to be instantaneously constant, the velocity and acceleration of the design could be correlated to the time needed as shown in Eq. 6.

$$\Delta t = \frac{\Delta v}{a} \tag{6}$$

The precise time needed to travel the necessary distance was then calculated by comparing the time value to the distance travelled. This optimization was done in an effort to get the vehicle as close to terminal velocity as possible for this event. The result was that the optimal gear ratio was beyond the 1:3 maximum ratio described in the project constraints. As such, the maximum ratio of 1:3 was chosen. This value was never revisited throughout the rest of the design process as it was soundly chosen using first principles of engineering. Knowing that the gear ratio could not be further optimized without changing the one-stage shifting set-up of the design, no further action was taken. It was determined that the added complexity of the two-stage shifting design in conjunction with the project time constraints made the potential design change unfeasible. This gear ratio was thereafter solidified for the remainder of the project and would become a building block from which all gearbox components would be based.

Similarly, the gear ratio was optimized for the hill-climb event. The optimization started with a free body diagram of the vehicle on a flat surface. An excel table and basic trigonometry was used to determine the free body diagrams force values at every angle from 0˚ to 45˚. From there the output torque point was selected on the motor torque vs. wheel speed and the output force was calculated. Then, it was simply a matter of looking at the resistive forces that increased as the vehicles angle increased and the applied force from the motor. At the point where the forces cancelled out was determined to be where the vehicle would stop on the ramp. The required torque to reach the end of the curved ramp was approximately 7.62 Nm, but with our output torque of 2 Nm and our maximum gear ratio of 3, we were only able to produce 6 Nm of torque. This will allow the vehicle to reach an angle of approximately 34˚ or 0.64 metres. Without adding another stage onto our gearbox, this is the best our vehicle can do with the current design. Seeing as this is approximately 75% of the length of the track for this event, it was considered a success and not worth the redesign and the potential cost to other events success.

Having thoroughly explored the gear ratios and come to sound conclusions for each event, these values were used to calculate all relevant dimensions and forces on the gears. These dimensions were the basis for the gears designed in Phase 1 and those designed in this final report. One minor change with respect to the gears are the addition of lightening holes to the Phase 4 design. As was discovered in Phase 2 of this project, the safety factor on the gears using the specified module of 1.75 mm and a face width of 10 mm was 9.71. This is far greater than it needed to be, meaning that the design was drastically over-engineered for its purpose. As such, the design decision was made to remove some material in an effort to reduce mass and minimize print while maintaining structural integrity. Due to the time constraints of this project, these lightening holes did not have their designs optimized by calculating precisely the material that would be needed to achieve a specific safety factor. Rather, the decision was made to remove sufficient material such that the mass and print time could be materially reduced, while the team remained confident in the structural integrity of the gear part. The team remained confident based on literature suggesting that lightening holes of the scale in the final design (relative to overall gear size) have a relatively small impact on the stress that the gear is able to withstand [1]. Going forward the optimization of lightening holes should be further considered, as it is quite likely that these could be made larger and further reduce material cost and print time without sacrificing design integrity.

The shaft design was very important for this project because it determines how our gears sit in the gearbox. The shape and position of the shafts varies greatly depending on whether the gearbox is 1 or 2-stage and whether it is a shifting design or not. The group decided to pick a one stage, shifting gearbox as it was a fairly simple design which could easily fit within the tight size constraints of the project. Another reason the group did not choose a 2-stage gearbox is the 3D printing time constraint. A 2-stage gearbox would require printing almost twice as many components and would likely take us over the time-limit set for this project. The shafts were therefore designed to fit two gears each for our 1-stage, shifting design.

The shafts were initially designed with a keyway connection to the gears. For this phase of the project, splines were used instead. The splines offer a more consistent torque distribution which is beneficial for our switch from AISI 4130 Steel to ABS plastic. This change altered the shape of the shafts, however the original diameters along the length were maintained. The new design of the shafts is significantly better for the design especially with the material change for the 3D printing that will occur after this phase. Factor of safety calculations were performed for the shafts based on the material properties and Equation 8 and 9 below. The factors of safety were found to all be greater than 1 which is sufficient for this project.

$$n_b = \frac{S_t^{Corrected}}{\sigma_b} \tag{8}$$

$$n_c = \frac{S_c^{Corrected}}{\sigma_c} \tag{9}$$

There were only relatively small changes made to the core design components: gears and shafts from Phase 1. For this phase, two entirely new components are being added to complete the design: the housing and bushings. The housing design was created not only to meet the multitude of design constraints to which it is subjected, but also to allow for a relatively simple assembly while minimizing mass and print time. It is for this reason that a four-walled support structure was avoided, and a multitude of crossbeams to provide support for two housing walls was pursued instead. As was briefly discussed in Section 2.0, each side of the housing essentially acts as a sandwich to lock in the core of the gearbox. The housing is designed to resist the slight expansion forces of the shafts by using crossbeams. This provides not only a rigid structure, but slight leeway with tolerances. All of this was done while taking a minimalist approach, wherein any sections that did not need material to provide structural support were eliminated to improve print time and lower material cost. The final new additional to the design that concluded the evolution of the gearbox was the bushing. The Oil-Embedded 841 Bronze Sleeve Bearings were selected as they perfectly suit our design while falling within the budgetary constraints.

4.0 Technical Specification

4.1 Assembly instructions

The print time of the final gearbox design is approximately 8 hours and 1 minute [Appendix E]. A summary table of the parts included in this design can be seen in Table 2**.**

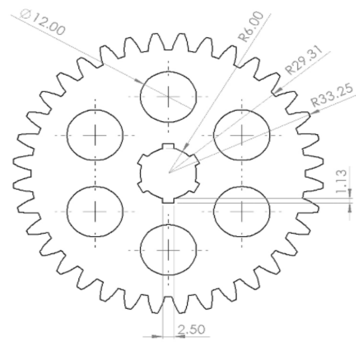
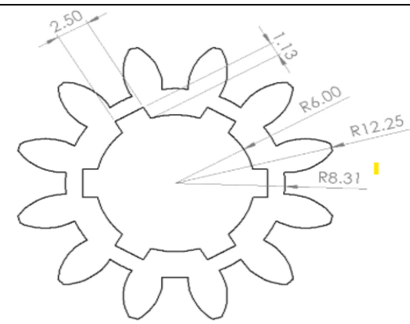
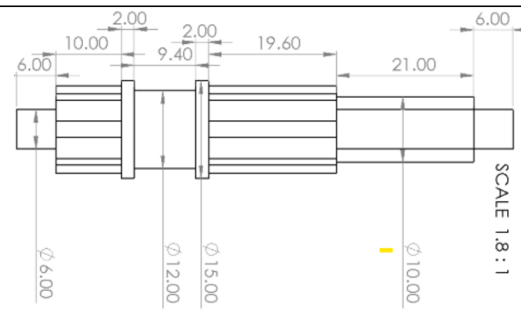
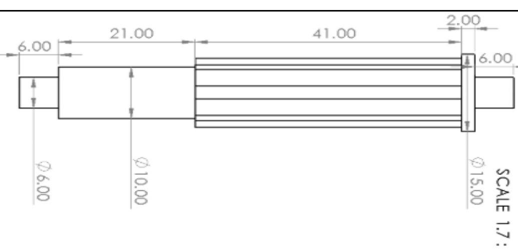
Table 2. A parts list for the final gearbox design.

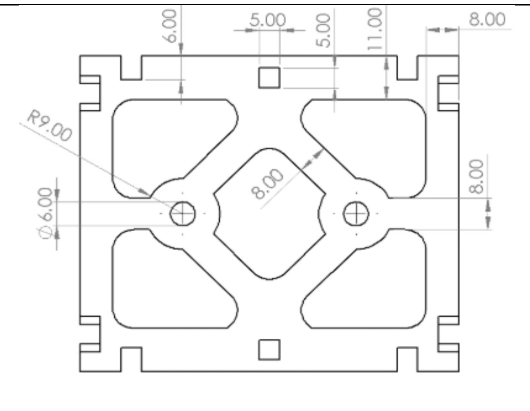
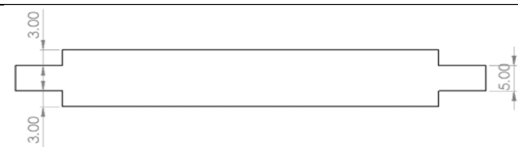
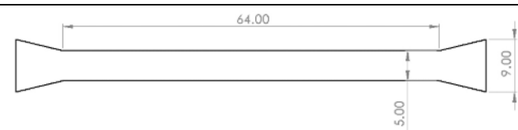
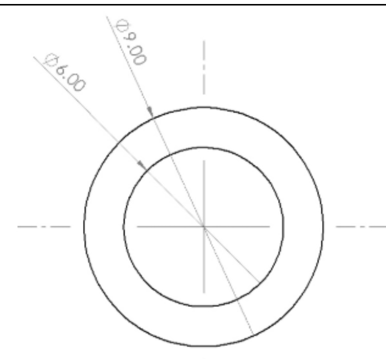
Part Number	Name	Part Count
1	36-tooth Gear	2
2	12-tooth Pinion	2
3	Input Shaft	1
4	Output Shaft	1
5	Side-Housing	2
6	Centre Crossbeam	2
7	Edge Crossbeam	4
8	6658K725 Bushing	4

The assembly of this design has been planned without the utilization of specialized tools in order to make it as simplistic as possible. The one exception to this is the potential use of sandpaper to remove any additional material that was accumulated on the parts in the printing process. The assembly procedure should take place as follows:

1. Remove the parts from the printing surface and sand off any excess material.
2. Place the gears and pinions onto the input shaft in accordance with the desired set-up (top-speed or hill climb), followed by the bushings.
3. Repeat step 2 for the output shaft, checking the alignment with the input shaft to ensure that the desired gears will mesh properly.
4. Place both shafts into the circular cut-outs of the right-hand side housing (the side without the torque pulleys).
5. Attach the centre crossbeams to the specified top and bottom locations of the housing.
6. Align the left-hand side housing with the shafts and centre crossbeams and attach.
7. To hold everything in place attach the four edge crossbeams using the dovetail joints.
8. Finally, attach the timing chains to the sprockets and begin the motor when ready to test the design.
9. Disassemble in the reverse order of these to shift the gear locations in preparations for the other event, then follow steps 2-7 once again.

4.2 Technical Specification Summary

Part Number	Name	Description	Drawing	Part Count
1	36-tooth Gear	The gears transmitting torque for the top speed event and engaged for the hill-climb event.		2
2	12-tooth Pinion	The pinons transmitting torque for the top speed event and engaged for the hill-climb event.		2
3	Input Shaft	Shaft used to receive input torque from the motor pulley.		1
4	Output Shaft	Shaft used to transmit torque to the output pulley.		1

5	Side-Housing	Housing design used to support input and output shafts.		2
6	Centre Crossbeam	Top and bottom beams connecting the centre of the left and right housing.		2
7	Edge Crossbeam	Edge beams connecting the four corners of the left and right housing.		4
8	6658K725 Bushing	Bushings used to		4

5.0 Future Work Recommendation

One of the primary challenges that the gearbox design had to solve is to simultaneously optimize performance in two events which require inversely proportional motor inputs. The design team attempted to solve this problem by creating a one-stage shifting gearbox where the gear ratios could be optimized for both events. However, the performance of the vehicle in both events was still imperfect, as the gear ratios were constrained to a maximum of 3:1. This constrains the gear ratio from being large enough or small enough to maximize performance in each event. In the future, a two-stage shifting gearbox should be selected. This adds additional complexity to the design, but with careful and thorough engineering practices being implemented, the design could be made sufficiently reliable and allow for an overall gear ratio of up to 9:1. This change would allow for a lower gear ratio in the top speed event, increasing the maximum velocity of the design and reducing its travel time, while allowing for a larger gear ratio in the hill-climb event to increase distance climbed.

While the performance of the gearbox is anticipated to be robust and effective, there are two key areas which should be carefully examined and improved upon. Each of these applies both for the printed plastic prototype, as well as for the potential scaled-up steel design. The first is the ease of manufacturing. This design has been meticulously thought out to maximize performance, but the ease of manufacturing has not been examined in detail to the same extent. Going forward this should be a significant factor in any design decisions. Not only do improvements in the ease of manufacturing improve reliability and reduce the potential for flaws in the manufacturing process, but it also helps reduce cost and manufacturing time. The second area that should be considered is the effect of the design on mass. While this was a consideration in the design process, due to time constraints it too was not fully examined. Going forward the potential reduction of mass should be analyzed through the partial hollowing of certain design components such as the shafts, as well as the further optimization of the lightening holes in the gears. These changes could have a significant impact on design performance by reducing rolling friction forces that are directly proportional to design mass, while maintaining structural integrity. A mass reduction such as this also has the potential to decrease material cost and improve manufacturing time.

In addition to these changes in design considerations, the design should be prototyped and rigorously tested. This will allow for any unanticipated design flaws to be discovered and provide opportunity for new design improvements to be made.

6.0 Drawing Package

6.1 Gearbox Assembly

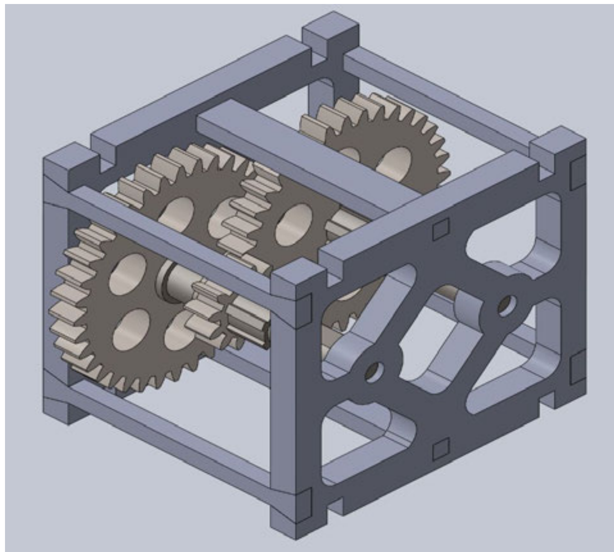
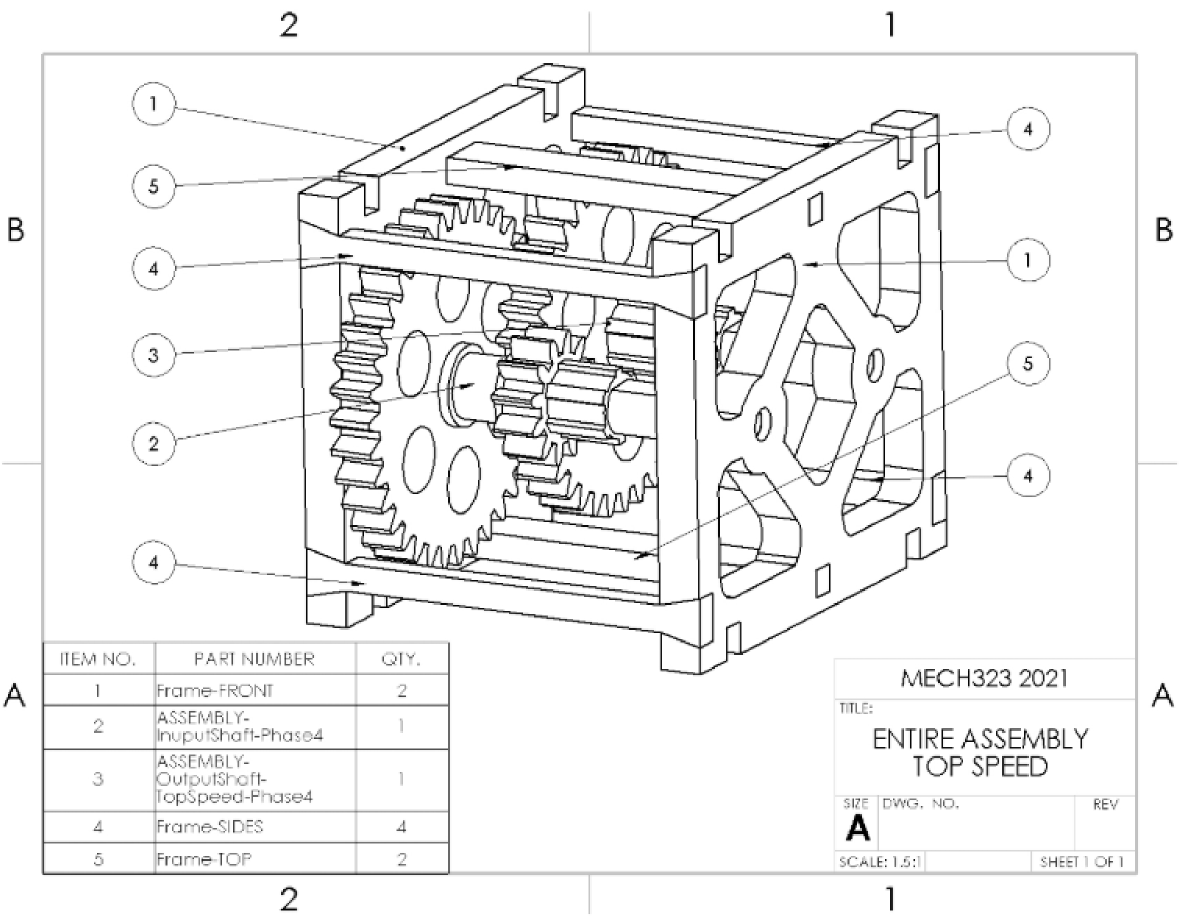


Table 3: CAD render of the entire gearbox assembly.



ITEM NO.	PART NUMBER	QTY.
1	Frame-FRONT	2
2	ASSEMBLY-InuputShaft-Phase4	1
3	ASSEMBLY-OutputShaft-TopSpeed-Phase4	1
4	Frame-SIDES	4
5	Frame-TOP	2

Table 4: CAD drawing of the entire gearbox assembly.

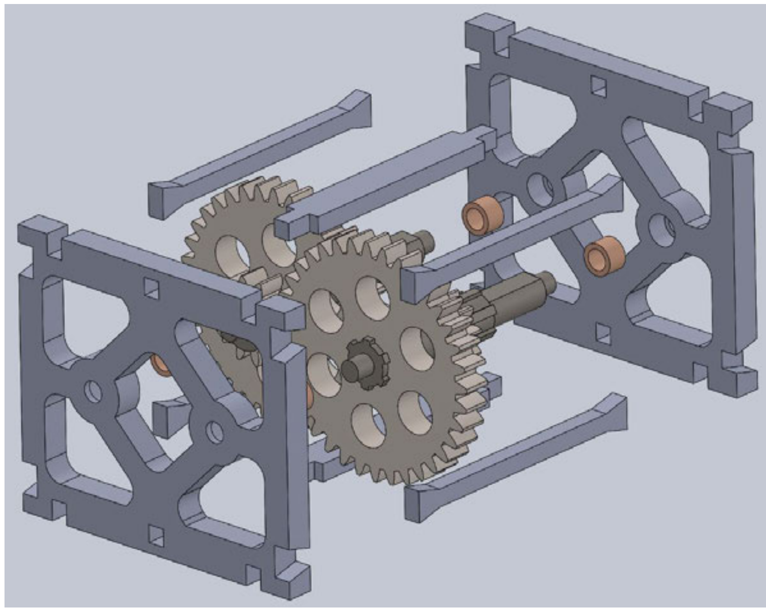


Table 5: CAD render exploded view of the entire gearbox assembly.

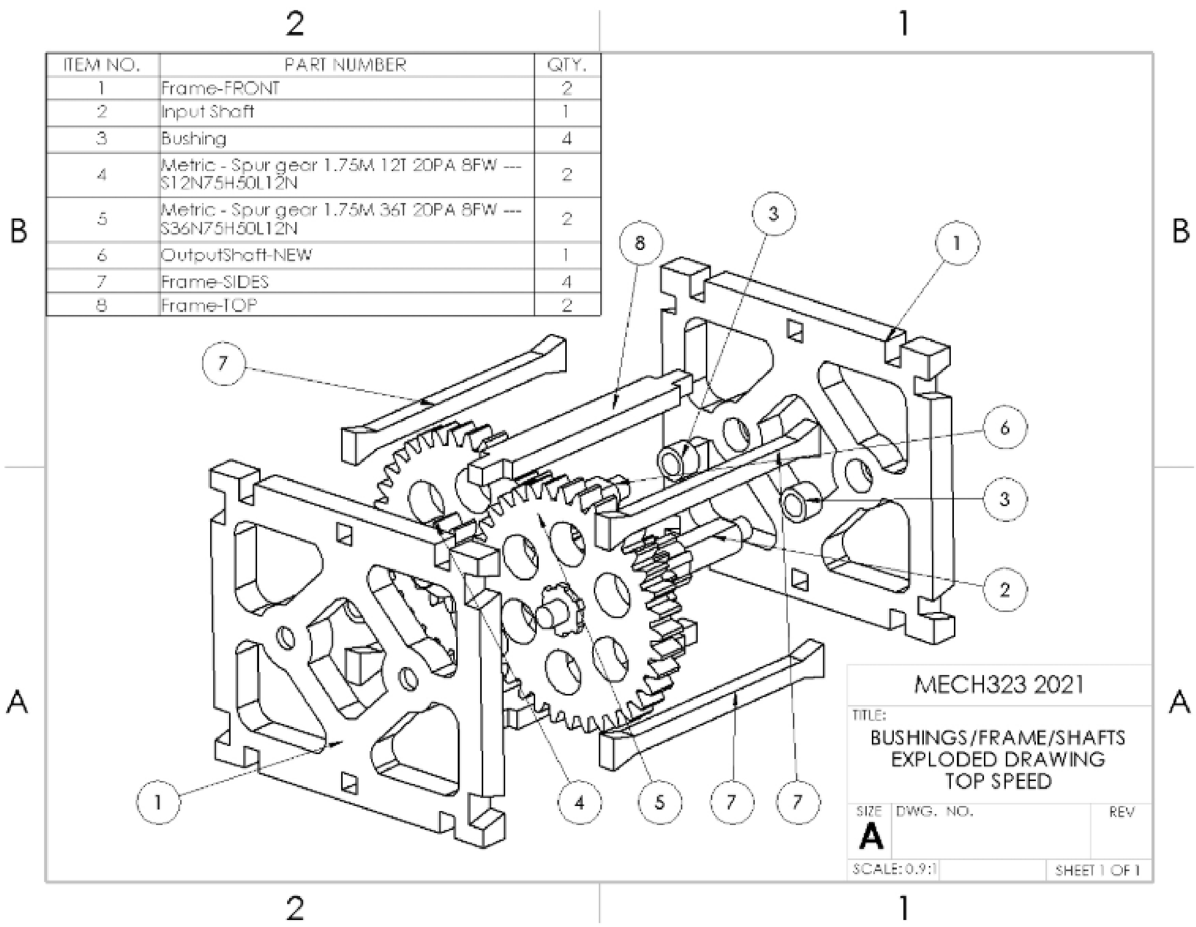


Table 6: CAD drawing of the exploded view of the entire gearbox assembly.

ITEM NO.	PART NUMBER	QTY.
1	Frame-FRONT	2
2	Input Shaft	1
3	Bushing	4
4	Metric - Spur gear 1.75M 12T 20PA 8FW --- S12N75H50L12N	2
5	Metric - Spur gear 1.75M 36T 20PA 8FW --- S36N75H50L12N	2
6	OutputShaft-NEW	1
7	Frame-SIDES	4
8	Frame-TOP	2

Table 7: Parts list for gearbox assembly.

6.2 Gears

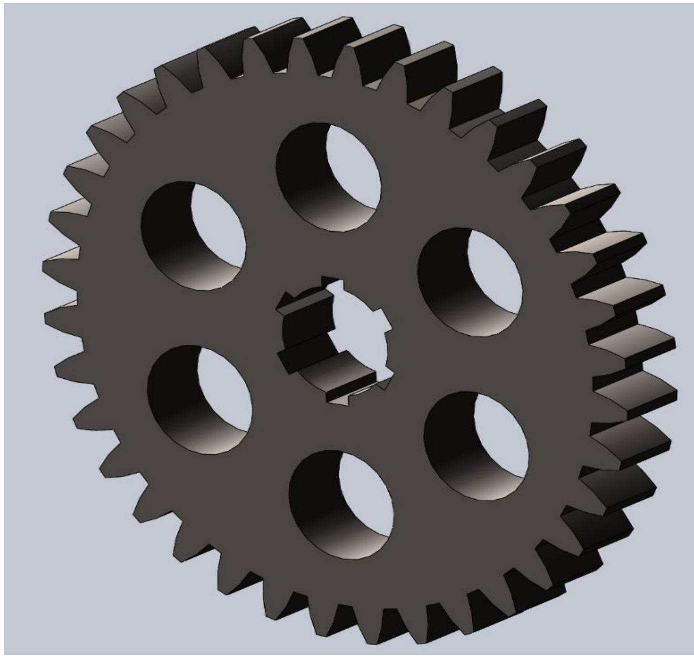


Table 8: CAD render of the gear used twice in the design (One on the input shaft for the top-speed event and once on the output shaft for the hill climb event).

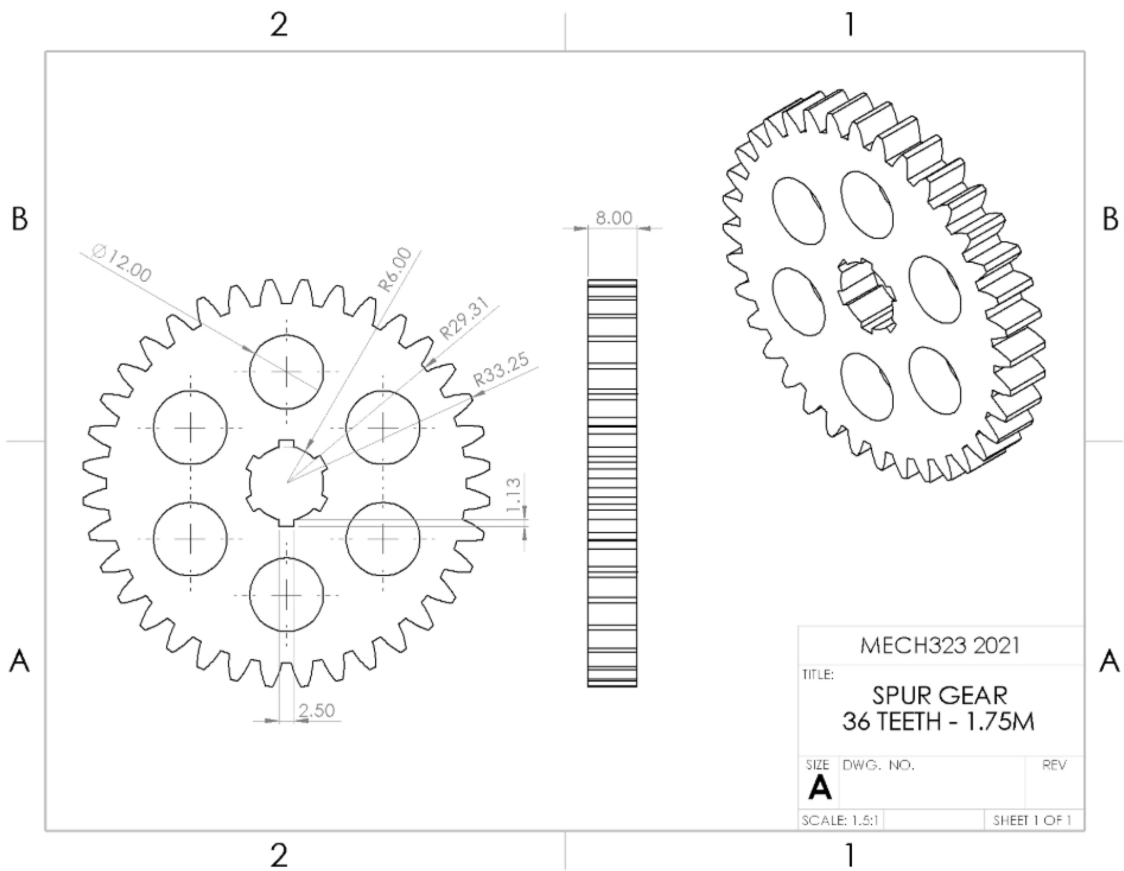


Table 9: CAD drawing of the gear used twice in the gearbox.

6.3 Pinions

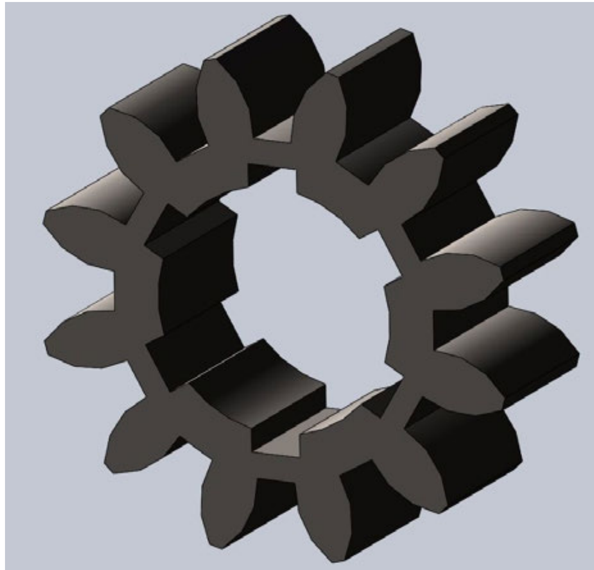


Table 10: CAD render of the pinion used twice in the gearbox (one on the input shaft for the hill climb event and once on the output shaft for the top-speed event).

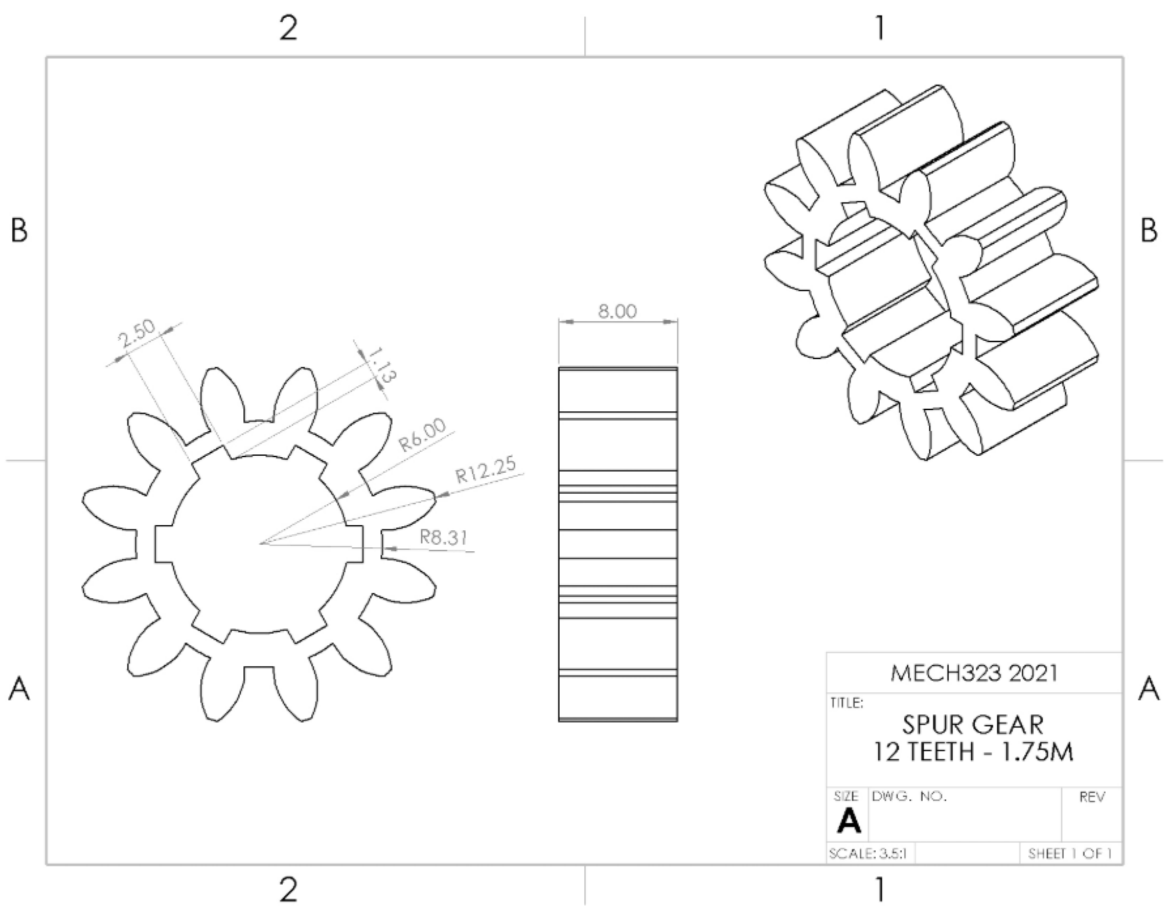


Table 11: CAD drawing of the pinion used twice in the gearbox.

6.4 Housing Components

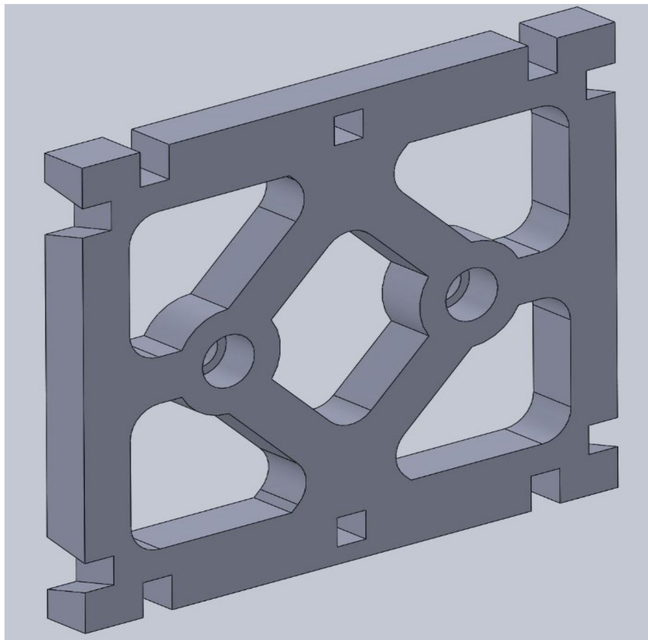


Table 12: CAD render of the side of the gearbox housing.

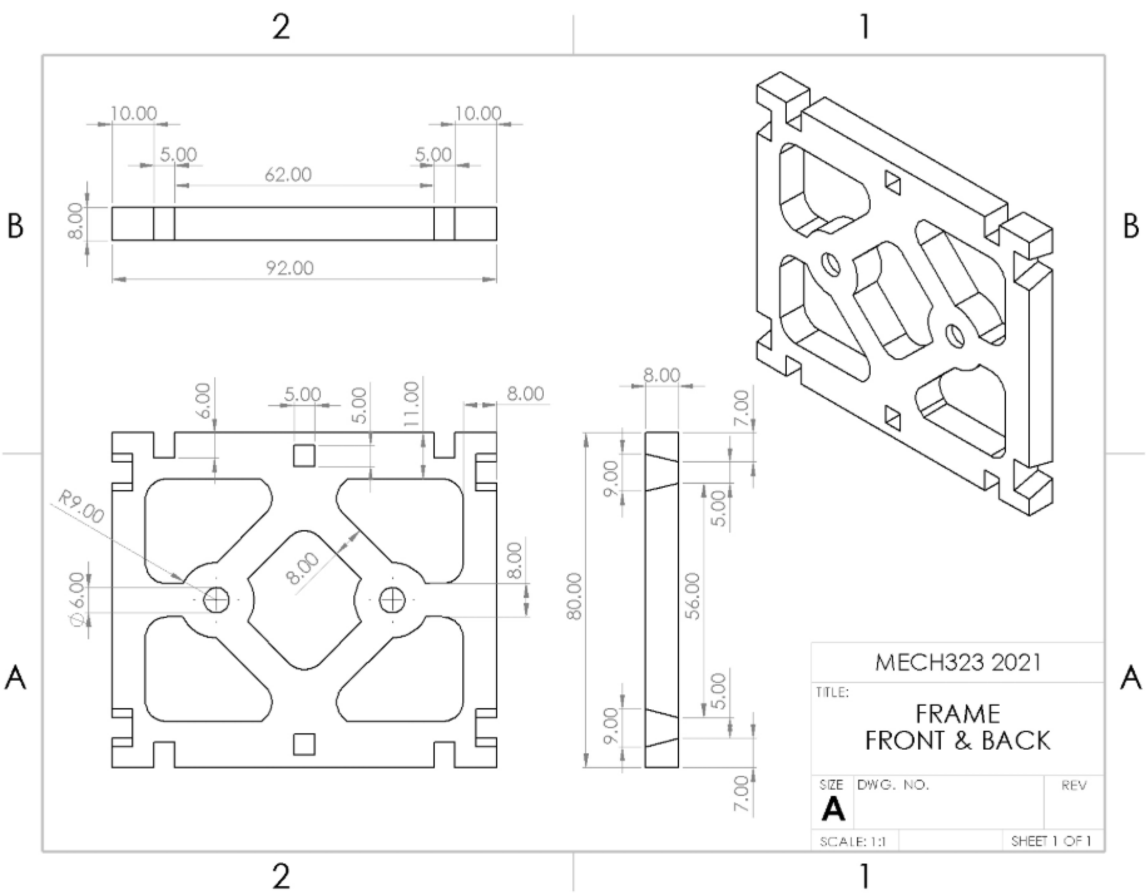


Table 13: CAD drawing of the side of the gearbox housing.

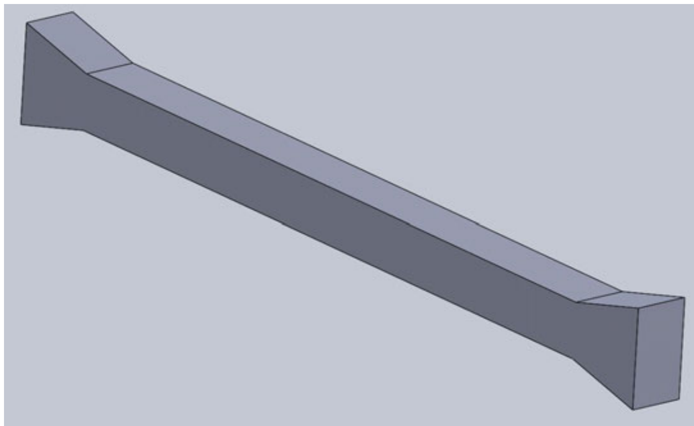


Table 14: CAD render of the dovetail connecting beam used in the corners of the gearbox housing.

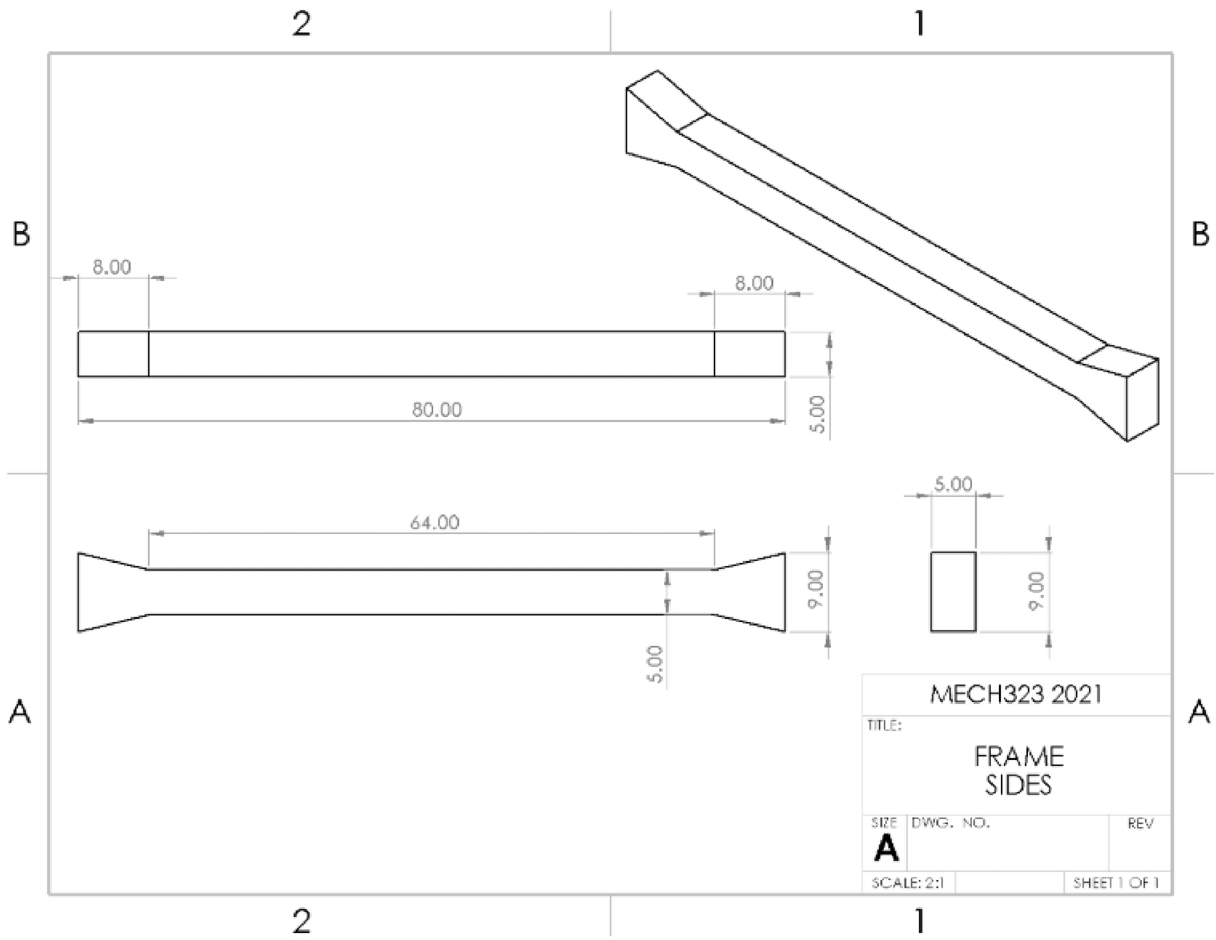


Table 15: CAD drawing of the dovetail connecting beam used in the corners of the gearbox housing.

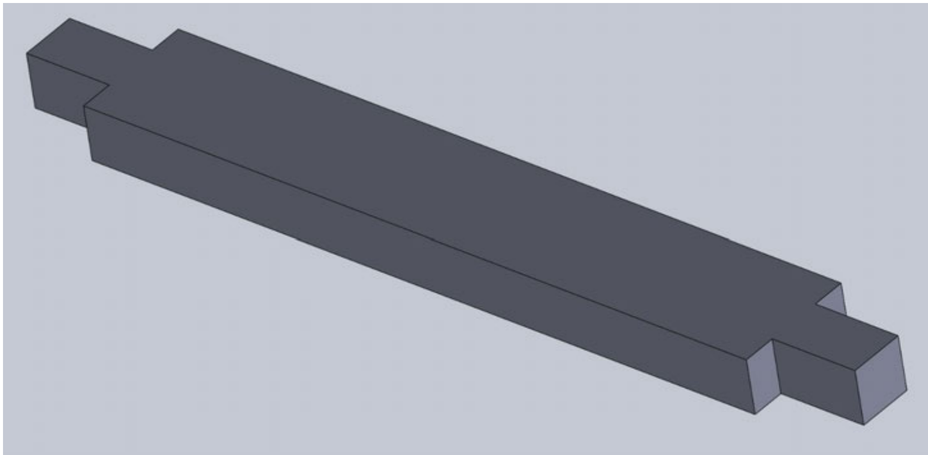


Table 16: CAD render of the non-dovetail connecting beam used on the top and bottom of the gearbox housing.

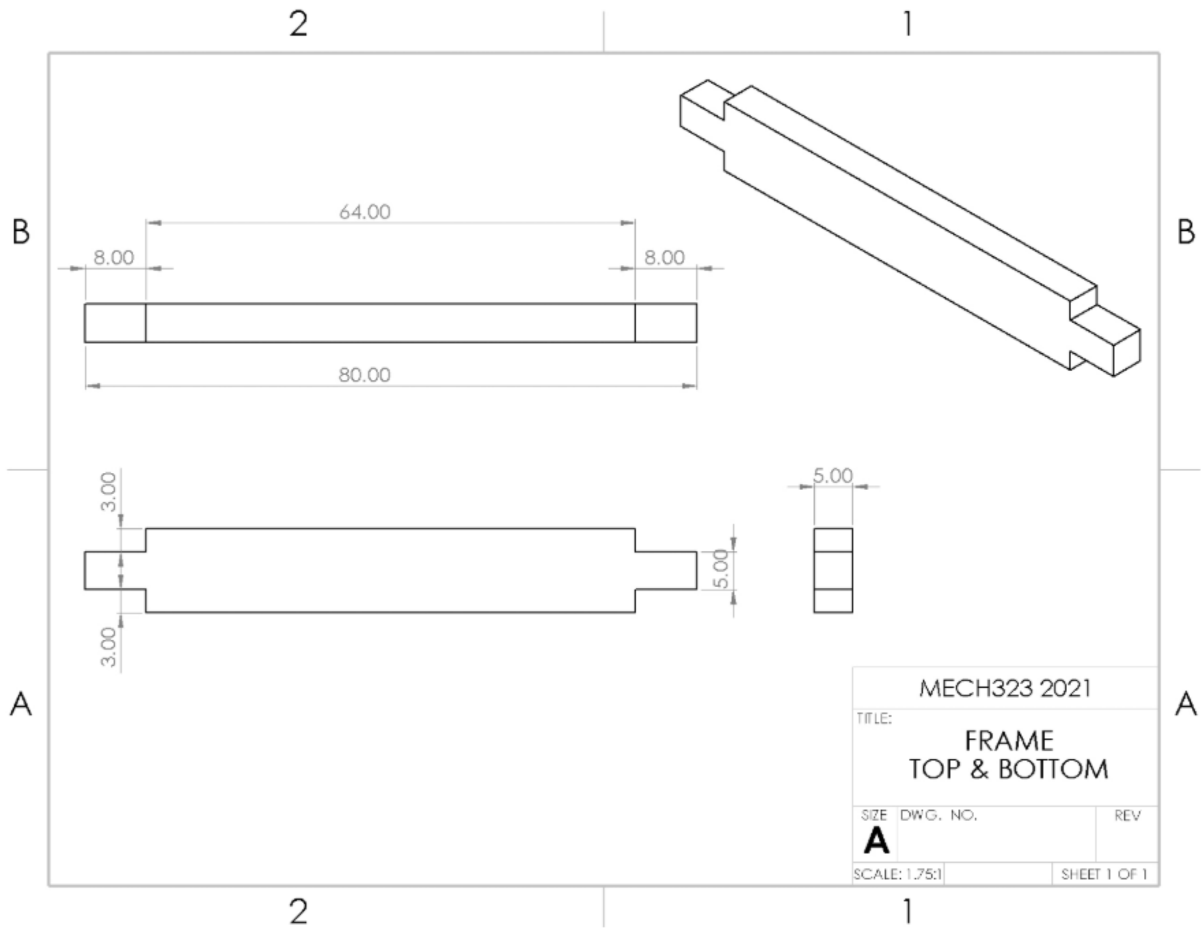


Table 17: CAD drawing of the non-dovetail connecting beam used on the top and bottom of the gearbox housing.

6.4 Bushings

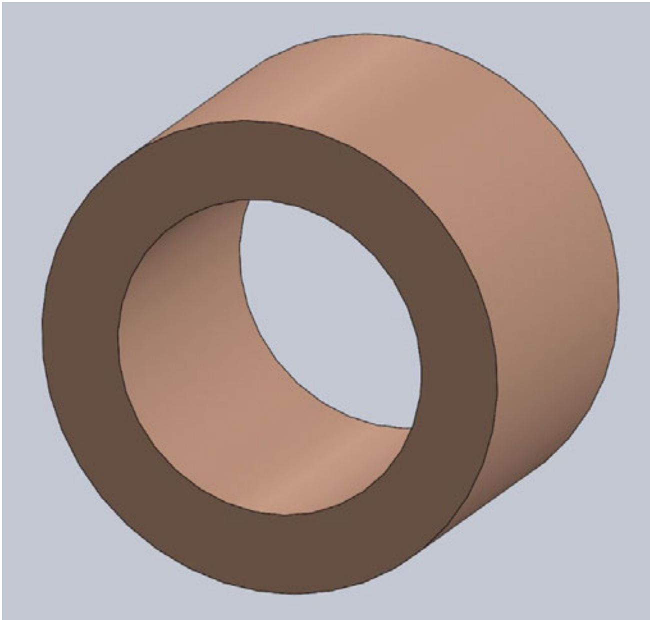


Table 18: CAD render of the bushing used for this project.

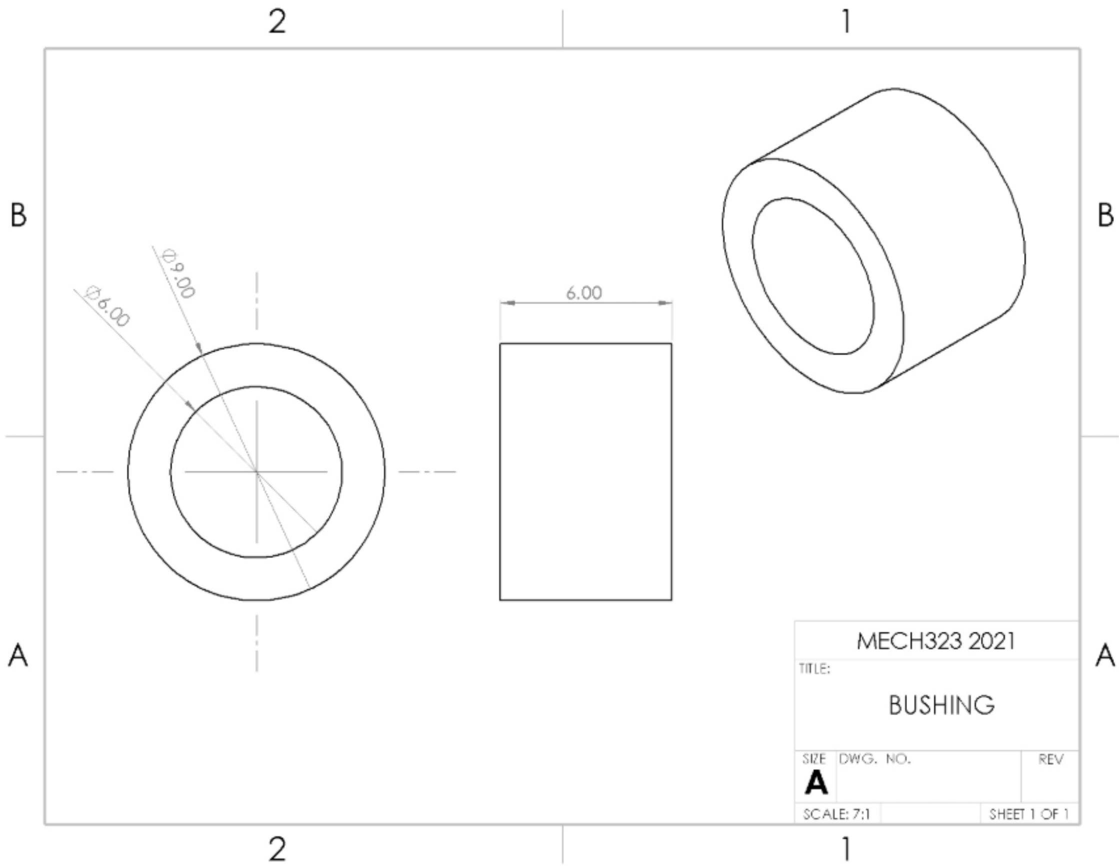


Table 19: CAD drawing of the bushing used for this project.

6.5 Gears, Shaft Assembly

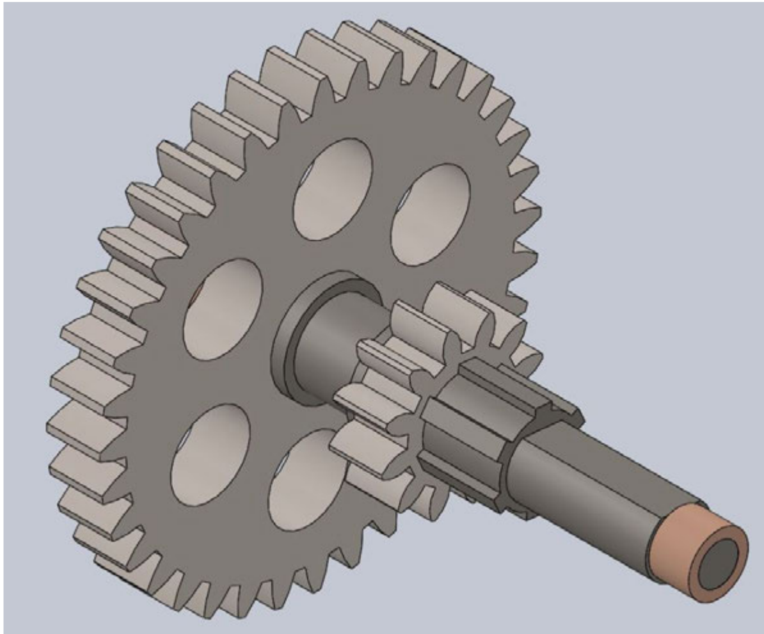


Table 20: CAD render of the input shaft assembly.

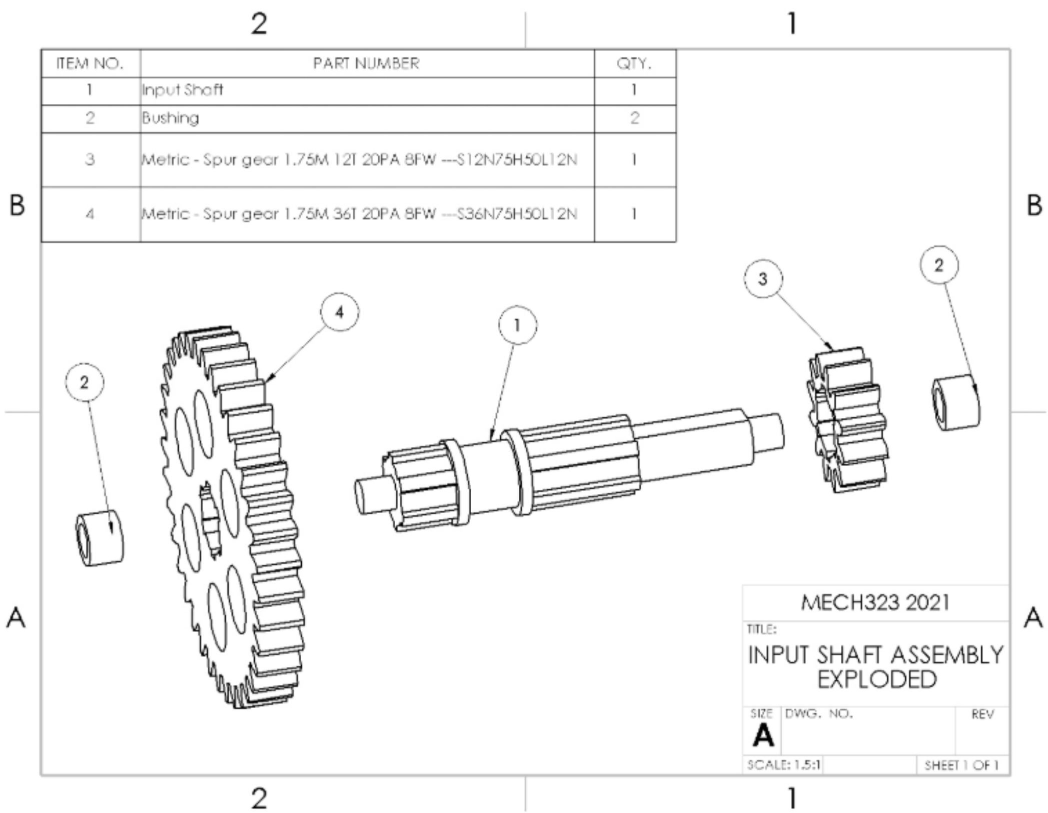


Table 21: CAD drawing of the input shaft assembly.

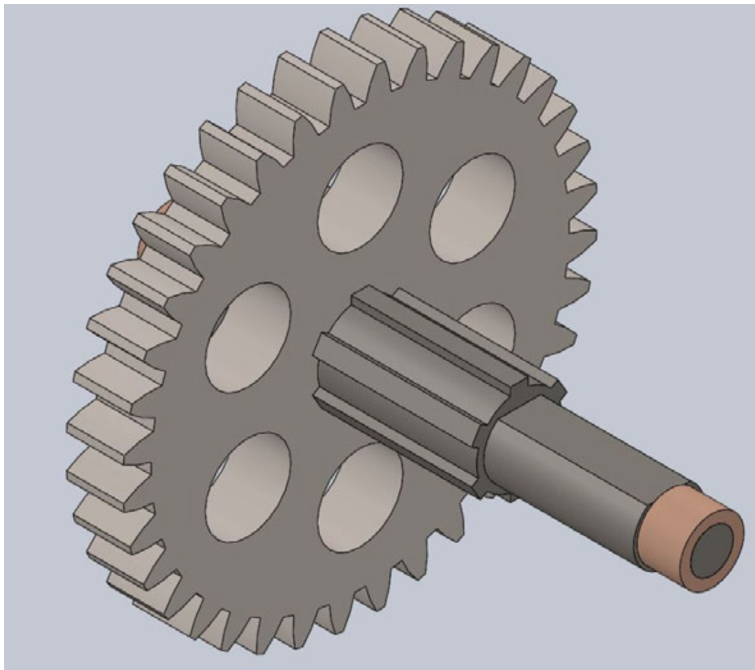


Table 22: CAD render of the output shaft assembly.

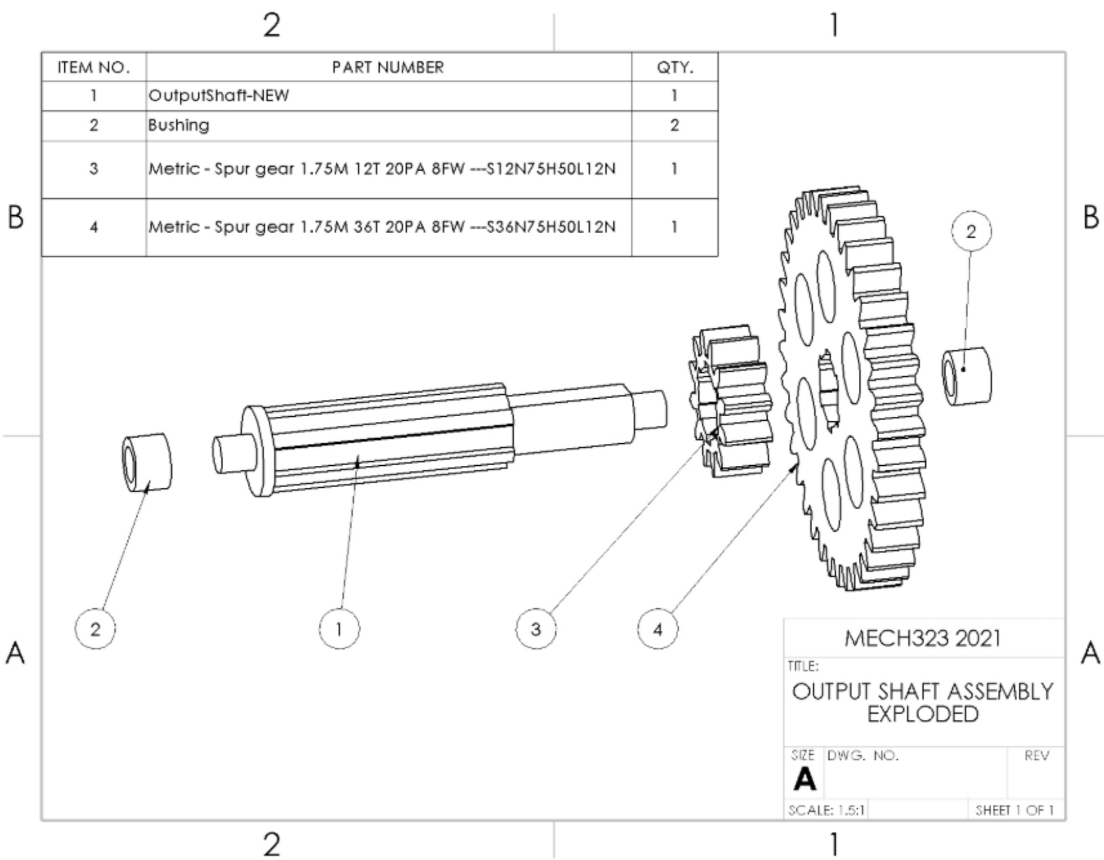


Table 23: CAD drawing of the output shaft assembly.

Bibliography

[1] Z. Sonmez and E. Öztürk, "OPTIMIZATION OF LIGHTENING HOLE ON A SPUR GEAR OF AN AIRCRAFT MOTOR," Sep. 2019.

Appendix A
Summary

Phase 1 Summary Page

(Attach to the end of your Phase 1 Report on a separate page)

Team Number	**2**

Phase Number	**2**

Global Design Characteristics		
Gear Box Parameters	**Number of Stages**	**1**
	Speed Gear Ratio	**1:3**
	Hill Climb Gear Ratio	**3:1**
Vehicle Weights	**Number of Weights Added**	0

Predicted Event Performance		
Speed Event	**2m Time (s)**	**0.595 s**
	Top Speed (m/s)	**3.73 m/s**
	Motor Operating Torque (Nm)	**0.775 Nm**
	Motor Operating Speed (rpm)	**60**
Hill Climb Event	**Distance (m)**	**0.62 m**

Appendix B

Image of Vehicle

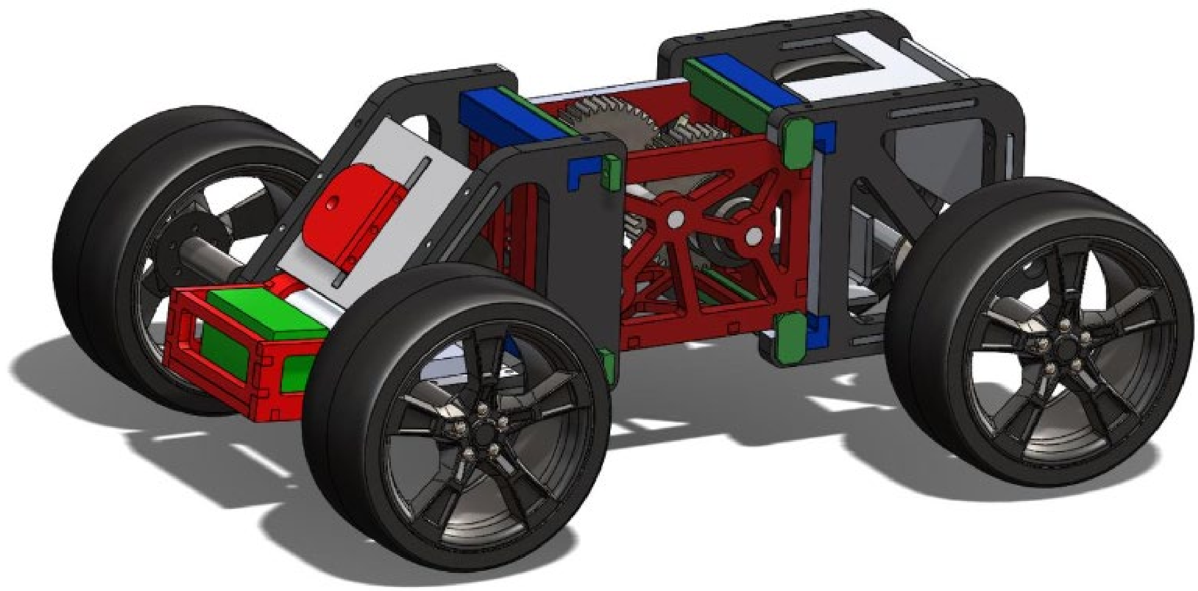


Figure 7: Image of the vehicle that the gearbox is being designed for.

Appendix C

Top Speed Test Diagram

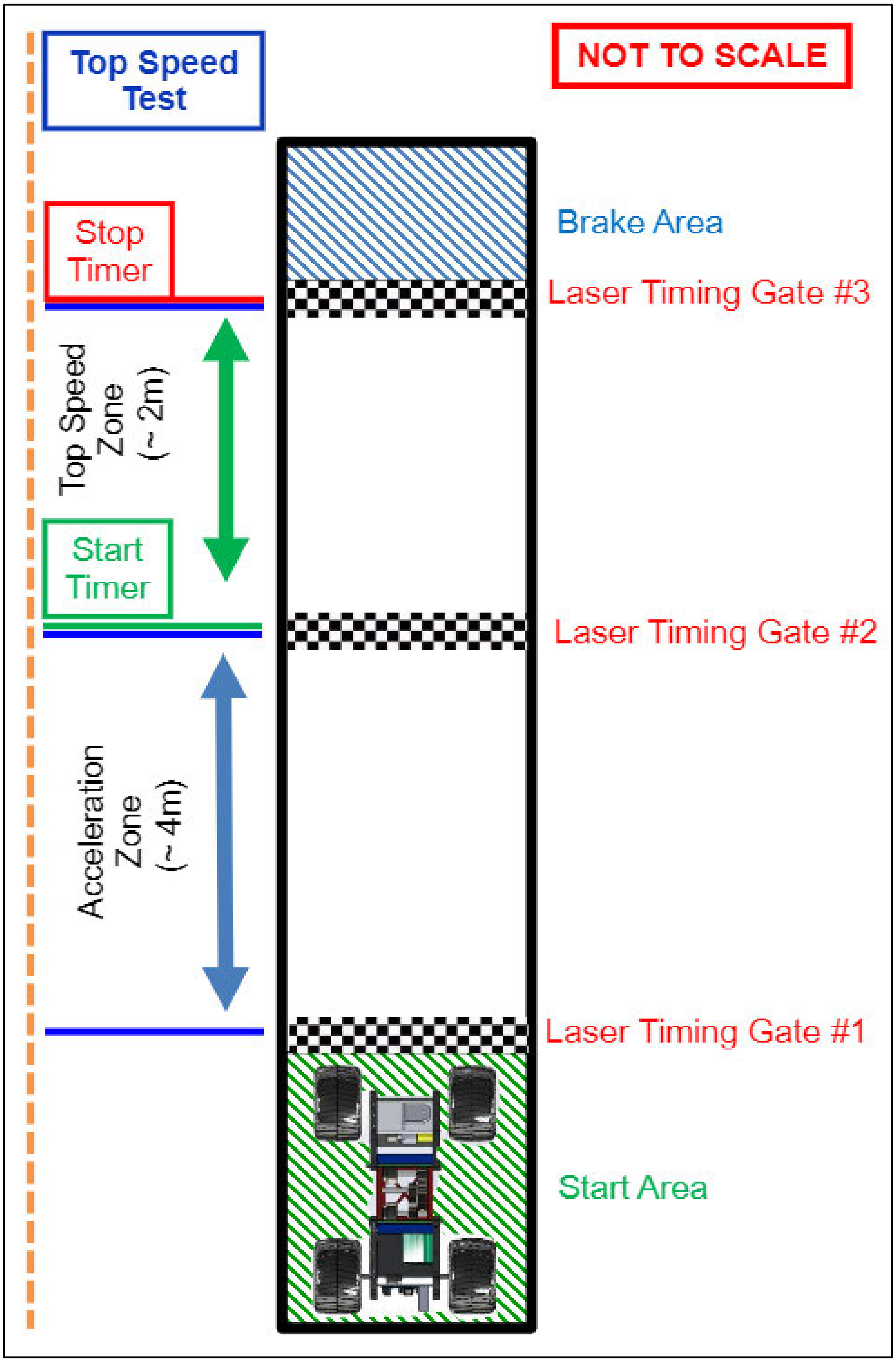


Figure 8: Diagram of the setup for the top speed test. Not to scale.

Appendix D

Hill Climb Event Diagram

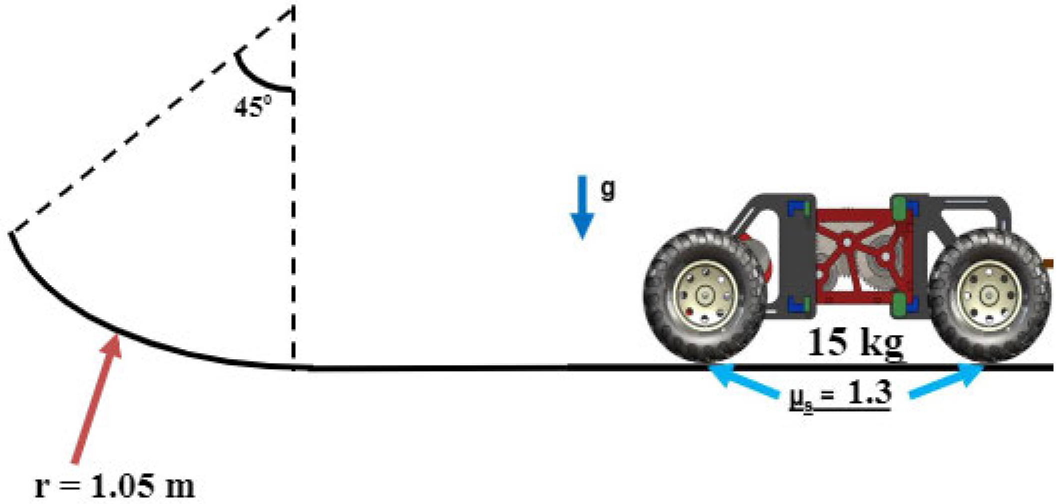


Figure 9: Diagram for the hill climb event. Not to scale.

Appendix E

3D Printing Information

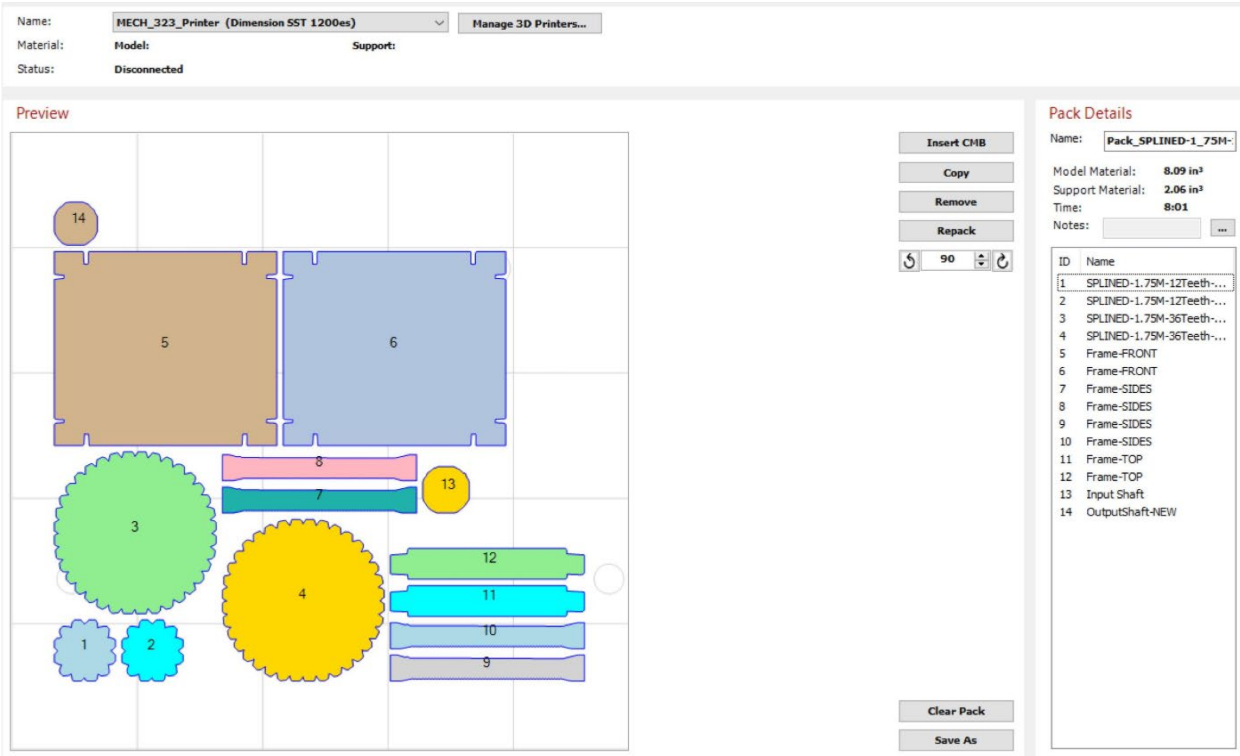


Table 24: 3D printing sheet for the projects final design.